Nature Climate Change Volume 6, pp 885 – 890 (2016),
DOI: doi:10.1038/nclimate3039

Climate change impact modelling needs to include cross-sectoral interactions

Paula A. Harrison[1,2,*], Robert W. Dunford[1,2], Ian P. Holman[3] and Mark D.A. Rounsevell[4]

[1] *Centre for Ecology & Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster LA1 4AP, UK. Email: PaulaHarrison@ceh.ac.uk*

[2] *Environmental Change Institute, University of Oxford, South Parks Road, Oxford, OX1 3QY, UK. Email: Robert.Dunford@ouce.ox.ac.uk*

[3] *Cranfield Water Science Institute, Cranfield University, Cranfield, Bedford, MK43 0AL, UK Email: I.Holman@cranfield.ac.uk*

[4] *School of GeoSciences, The University of Edinburgh, Drummond Street, Edinburgh, EH8 9XP, UK Email: Mark.Rounsevell@ed.ac.uk*

* Contact information: Email = PaulaHarrison@ceh.ac.uk; Tel: +44 1524 595858.

Abstract

Climate change impact assessments often apply models of individual sectors such as agriculture, forestry and water use without considering interactions between these sectors. This is likely to lead to misrepresentation of impacts, and consequently to poor decisions about climate adaptation. However, no published research assesses the differences between impacts simulated by single sector and integrated models. Here we compare 14 indicators derived from a set of impact models run within single sector and integrated frameworks across a range of climate and socio-economic scenarios in Europe. We show that single sector studies misrepresent the spatial pattern, direction and magnitude of most impacts because they omit the complex interdependencies within human and environmental systems. The discrepancies are particularly pronounced for indicators such as food production and water exploitation which are highly influenced by other sectors through changes in demand, land suitability and resource competition. Furthermore, the discrepancies are greater under different socio-economic scenarios than different climate scenarios, and at the sub-regional rather than Europe-wide scale.

The Intergovernmental Panel on Climate Change (IPCC) has stated the need and importance of undertaking integrated, cross-sectoral assessments of climate change impacts in order to account for the indirect effects of climate change. This is a prerequisite for any type of comprehensive climate impact assessment that aims to inform adaptation or mitigation planning. However, as the IPCC Fifth Assessment report (AR5)[1] states: "*Little information is available on integrated and cross-sectoral climate change impacts in Europe, as the impact studies typically describe a single sector […]. This is a major barrier in developing successful evidence-based adaptation strategies that are cost-effective*." Impact assessments that do not account for cross-sectoral interactions have the potential to misrepresent impacts and thus, the need or otherwise for adaptive action. This misrepresentation is likely to be reflected in an over- or under-estimation of impacts with the magnitude of these differences varying through time and across space.

Impacts resulting from future socio-economic change have been shown, in some cases, to be greater than impacts based on future climate change alone[2,3,4,5,6]. It is often through the socio-economic drivers that cross-sectoral impacts become evident, as policy effects in one sector can have indirect effects in others, and these effects are lost in single sector studies. Given this situation, it is perhaps surprising that many impact studies continue with a single sector emphasis, e.g. the Agricultural Model Intercomparison and Improvement Project (AgMIP)[7] and most of the studies reported in the IPCC AR5[8,9]. This could in part be due to the predominantly disciplinary nature of climate impacts research, whereas multidisciplinary and transdisciplinary approaches are essential for understanding the complexity of cross-sectoral interactions. However, whilst the importance of integrated approaches is becoming recognised[10,11], it could also be related to a lack of knowledge about the significance of such cross-sectoral interactions for understanding the magnitude and spatial distribution of future impacts, as no studies have evaluated the discrepancies arising from a single sector approach.

Here we demonstrate the importance of an integrated approach to climate change impact assessment by comparing indicators derived from a common set of impact models run within a single sector framework and an integrated framework that accounts for cross-sectoral interactions. The analysis uses the CLIMSAVE Integrated Assessment Platform (IAP[12,13]), which links models of agriculture, forestry, urban growth, land use, water resources, flooding and biodiversity. The IAP is a spatially-explicit modelling platform that operates on a 10 x 10 minute grid for the countries of the European Union plus Norway and Switzerland. It has been thoroughly validated (Supplementary Table 1) and widely applied in climate change impact[2,4,6,14,15], adaptation[16] and vulnerability[17] assessment, in robust policy analysis[18], and has been tested extensively through model sensitivity[19] and uncertainty analysis[20,21]. It was applied with and without coupling of the individual sectoral models for a number of scenario experiments for the 2050s that included different SRES emissions scenarios[22], climate change models[23] and the socio-economic storylines underlying the SRES scenarios[22]. Differences between the single sector and integrated model results for a number of impact indicators were determined and analysed statistically for significance of difference.

Climate change impacts from single sector studies

We recognise that climate change impact results are strongly influenced by the choice of impact model[24], even when models have been well validated against historical observations. Thus, we have carried out a benchmarking exercise (see Supplementary Table 2 and associated text) to test the pertinence of the single sector models within the IAP with respect to current knowledge from the literature, by demonstrating that the models can replicate the types of European impact results summarised in the "Europe" chapter of the IPCC AR5[1] for a range of indicators.

Europe-wide model outcomes differences

Differences between impact indicators from running the IAP as a set of stand-alone single sector models and a fully coupled, integrated model including cross-sectoral interactions are shown in Figure 1 for all the scenario experiments. The figure shows the proportion of indicators that are identical across the two modelling approaches, but does not show the magnitude of difference between individual indicators. There are clear differences between the single sector and integrated models and across the scenarios, ranging from 3% (little agreement) to 100% (total agreement). In general, the greatest differences are seen for food provision and water exploitation, and the smallest differences for the forest-related indicators and urban land cover. This reflects the degree of influence that other sectors have on each indicator. For example, in the integrated model allocation of land for urban development is assumed to take precedence over other land uses, and so other sectors do not affect urban development and there are no differences between the single sector and integrated model outcomes for this indicator. Forestry indicators differ little between scenarios, as it is assumed that current tree species do not adapt to climate change. Hence, there is little expansion in forestry in either the single sector or integrated model runs as tree species become stressed with climate change and forestry struggles to compete with other land uses based on profitability.

Conversely, food production and water exploitation are highly influenced by other sectors through changes in demand, land suitability and competition for land. For example, the agricultural area needed for food production is affected by widespread (albeit small) changes in urbanisation as well as changes in the frequency of flooding which alters the land suitability for different farming activities. Furthermore, changes in irrigation water availability influence the selection of irrigated and non-irrigated crops grown in an area which in turn affects agricultural profitability and food production. Similarly, water exploitation has significant influences from changes in irrigation use in the agricultural sector as well as competing demands for water from domestic and other sectors as reflected by changing population patterns in the urban model. Biodiversity indicators vary between single sector and integrated models, depending on how land use changes from other sectors, such as agriculture and forestry, affect the habitats for particular species.

Figure 1 also shows how the differences between single sector and integrated models vary depending on the type of scenario. Around half of the indicator-scenario combinations have more than 80% identical values with different climate models (39 out of 70 [54%]; panel 1 in Figure 1) and different emissions scenarios (32 out of 56 [57%]; panel 2) when socio-economic conditions remain unchanged. However, only 21 out of 56 [38%] (panel 3) and 26 of 70 [37%] (panel 4) of indicator-scenario combinations have more than 80% identical values with the future socio-economic scenarios. This is because changes in socio-economic drivers, such as population, GDP, food imports and technology, stimulate greater interactions between the sectoral models. For example, under the A2 socio-economic scenario an increase in population combined with decreases in food imports and negligible improvements in technology leads to substantial land use change as agriculture expands in order to meet European food demand which in turn leads to large scale reductions in forest area, increases in irrigation usage and water exploitation, and greater vulnerability for species which are not associated with agricultural habitats. None of these cross-sectoral interactions which are stimulated by the socio-economic drivers are captured in the single sector stand-alone model runs.

The selection of climate model or emissions scenario has only a relatively minor effect on the variability of differences between single sector and integrated models for an individual impact indicator. This is shown by the relatively small range of values in the first and second panels of Figure 1. In contrast, uncertainties related to the inclusion of socio-economic scenarios with different climate models and emission scenarios result in a much greater range of differences between single sector and integrated models with seven indicators having ranges greater than 15% and four (food provision, unmanaged land, arable land and intensive agriculture) having ranges of more than 30% across the different socio-economic scenarios (panel 3).

Figure 2 shows the magnitude of the under- and over-estimation of the single sector models with respect to the integrated model across the range of scenarios. The differences arising from the range of climate models (5 models) and emissions scenarios (4 scenarios) are reflected as minimum and maximum values. Very few impact indicators have little or no difference (urban being the exception), so almost all of the indicators are to some extent over- or under-estimated by the single sector models. Some indicators have extremely high differences (over 100%) such as the water exploitation index and arable biodiversity. Other indicators have relatively large differences (25-100%) such as irrigation, forest biodiversity and people flooded. There are some differences between the climate, socio-economic and emissions scenarios for some, but not all, of the indicators. The results taken as a whole provide evidence in support of the basic premise presented here that single sector models misrepresent the full range of possible climate change impacts, and that this is reflected in both over- and under-estimation of impacts.

Sub-regional model outcomes differences

The IAP is a spatially-explicit model and so we are able to compare differences between the single sector and integrated models geographically. Figure 3 highlights how the inclusion of cross-sectoral interactions leads to very different spatial patterns for the indicators. The scenario (SRES A2) illustrated represents a hot, wet climate for Europe with a large increase in population (+25%), a decrease in food imports (-10%) and no water savings from technological or behavioural change (Supplementary Table 3). The integrated model run shows greater water exploitation values across river basins in much of southern, central and eastern Europe than the single sector model runs due to a simulated increase in irrigation which becomes profitable due to the pressure of meeting food demand with a higher population and reduced imports. However, the spatial distribution of food production varies between the single sector and integrated model runs. The single sector runs show higher levels of irrigated food production in much of Spain and central to eastern Europe, whilst in the integrated run food production increases to a greater extent in Fennoscandia where irrigation is not needed but climate conditions have improved sufficiently to support more agricultural production. This leads to both a reduction in forest cover in northern Europe as forests are converted to agriculture and an increase in forest production in areas where food production has decreased. In southern Spain, this reduced need for irrigation leads to less water exploitation compared to the single sector model outputs.

Figure 4 shows sub-regional differences between single sector and integrated model runs across a wider range of scenarios. All of the European sub-regions show large differences in both directions both with and without socio-economic changes. This arises because, as demonstrated in Figure 3, each combination of climate and socio-economic scenario leads to complex cross-sectoral interactions that the single sector models cannot take into account. For example, irrigation use changes significantly by scenario in the integrated model because it is able to adapt to dynamic changes in crop yields and water availability in a way that the single sector models, with static inputs for these variables, cannot. As such under the GFCM21 climate model with baseline socio-economic parameters, irrigation is shown to have both positive and negative differences (>5%) from the single sector models in the northern, Atlantic and continental regions depending on the SRES emissions scenario. The changing profitability of irrigated crops has indirect impacts on many of the land use indicators such as arable land, intensive agriculture, extensive grassland and unmanaged land which also show both positive and negative differences (>5%) depending on the scenario. Under the IPCM4 climate model, where changes in precipitation are less marked, there are fewer differences between the single sector and integrated models, but some differences remain, particularly for food production and irrigation (Supplementary Figure 1).

Sub-regional differences between single sector and integrated models greatly increase when socio-economic changes are included in the scenarios shown in Figure 4 as drivers such as population growth, GDP, technological change (for water savings, irrigation efficiency and crop yields) and behavioural change (for water savings and dietary preferences) have differential influences on the sectoral models in the modelling chain. Increasing or decreasing water savings in the water model, for example, can significantly alter the amount of water available for irrigation, modifying the profitability of agriculture and the spatial pattern of irrigation use, and resulting in indirect impacts for other land uses (such as forestry) and for biodiversity depending on the habitats these land uses support.

Benefits of integrated modelling approaches

Comparing differences in the IAP indicators when computed using a single sector vs integrated modelling approach highlights the implications of relying solely on sectoral models (Figure 5). For most indicators, both single sector and integrated models project the same direction of change relative to baseline. However, there are cases where the direction of change projected by single sector models is the opposite of that projected for the integrated model; this includes water exploitation, people flooded, arable land, intensive agriculture, extensive grassland, carbon storage and biodiversity. This is particularly noticeable for agricultural indicators, where maximum European levels of arable, intensive agriculture and extensive agriculture are 62-72% of baseline levels in the single sector models and 118-156% of baseline values in the integrated model where cross-sectoral interactions are taken into consideration. This reflects the considerable changes in land use needed to meet food demand when additional pressures are placed on the agricultural system from other sectors, e.g. losses of high quality agricultural land due to urban expansion, changes in water availability for irrigation and changes in timber demand from forestry.

Furthermore, significant differences in the magnitude of change are apparent even when the single sector and integrated models agree on the direction of change relative to baseline. Of the maximum and minimum differences shown in Figure 5, 60% are more than $\pm 10\%_{BL}$ and 24% are more than $\pm 50\%_{BL}$ (see Figure 5 for explanation of units). Of those differences which are greater than $\pm 10\%$, 82% show that the indicator value from the integrated model is higher than from the single sector models.

The range of projections across the scenarios (between the minimum and maximum scenario values) also expands as a result of model integration. Across all indicator-region combinations the integrated model shows an increase in range of more than $10\%_{BL}$ in 58% of cases, and more than $50\%_{BL}$ in 27%. The variables with the greatest increase in range are the agricultural land use classes (intensive agriculture, extensive grassland, arable), abandoned land and irrigation, all of which have range expansions of more than $50\%_{BL}$ in multiple regions; the water exploitation index also increases in range by more than $50\%_{BL}$ in the continental region. Contractions in projection ranges due to model integration are less common with no indicators showing reductions in range across all regions. However, the range of outcomes for food provision and carbon storage reduce by more than $25\%_{BL}$ in a number of regions, particularly the northern and alpine regions.

The IAP takes a largely linear approach to data transfer within the impact model chain that only includes limited feedbacks when applied within a single simulation round and assumes that the consequences of cross-sectoral interactions manifest themselves within the 30-year timeslice. Given these limitations and the widely recognised uncertainty within impact models themselves, a different modelling approach would inevitably generate results that differ in the magnitude and spatial patterns of the impact differences reported here. However, we believe that such modelling differences would not change the overall system understanding which is gained by the *a priori* implementation of cross-sectoral interactions directly within modelling frameworks, rather than considering cross-sectoral interactions as an *a posteriori* discussion of sectoral impact results[25].

Single sector impact models that ignore the complex interdependencies present in human and environmental systems will generally inadequately represent the spatial patterns, directions and magnitudes of most indicators of climate-sensitive impacts. Whilst the choice of climate model and emissions scenario introduces differences in impact results between single sector and integrated impact models, these effects are dwarfed by the consequences of highly uncertain future socio-economic change. These arise due to the high sensitivity of some elements of environmental systems to socio-economic drivers (such as rural land use allocation), and the way in which such effects propagate through the dependencies within an integrated modelling system. Furthermore, this analysis has demonstrated quantitatively for the first time the uncertainty arising from a siloed, single sector perspective and cautions against the use of outputs from sectoral models to inform adaptation policy. This highlights the importance of developing adaptation plans that are robust to changes in climate and socio-economic pathways and that take account of cross-sectoral interactions.

References

1. Kovats, S. *et al*. (2014) *IPCC AR5 Chapter 23, Europe*, online resource available at http://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-Chap23_FGDall.pdf, Accessed 21/8/2015.
2. Audsley, E., Trnka, M., Sabaté, S., Sanchez, A. Interactive modelling of land profitability to estimate European agricultural and forest land use under future scenarios of climate, socio-economics and adaptation. *Clim. Chang.* **128,** 215-227 (2015).
3. Audsley, E., Pearn, K.R., Harrison, P. A., Berry, P. M. The impact of future socio-economic and climate changes on agricultural land use and the wider environment in East Anglia and North West England using a meta-model system. *Clim. Chang.* **90,** 57-88 (2008).
4. Holman, I. P., Harrison, P. A., Metzger, M. Cross-sectoral impacts of climate and socio-economic change in Scotland - implications for adaptation policy. *Reg. Environ. Chang.* **16,** 97-109 (2016).
5. Holman, I. P. *et al.* A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change in the UK: II Results. *Clim. Chang.* **80,** 43-73 (2005).
6. Wimmer, F. et al. Modelling the effects of cross-sectoral water allocation schemes in Europe. *Clim. Chang.* **128,** 229-244 (2015).
7. Rosenzweig, C. *et al.* The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agric. For. Meteor.* **170,** 166-182 (2013).

8. IPCC. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B. *et al.* (eds.)]. (Cambridge Univ. Press, 2014).

9. IPCC. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Barros, V.R. et al. (eds.)]. (Cambridge Univ. Press, 2014).

10. Huber, V. *et al.* Climate impact research: beyond patchwork. *Earth System Dynamics* **5**, 399-408 (2014).

11. Warren, R. The role of interactions in a world implementing adaptation and mitigation solutions to climate change. *Philos. T. R. Soc. A* **369**, 217-241 (2011).

12. Harrison, P. A, Holman, I. P., Berry, P. M. Assessing cross-sectoral climate change impacts, vulnerability and adaptation: an introduction to the CLIMSAVE project. *Clim. Chang.* **128,** 153-167 (2015).

13. Harrison, P. A. *et al.* Combining qualitative and quantitative understanding for exploring cross-sectoral climate change impacts, adaptation and vulnerability in Europe. *Reg. Environ. Chang.* **13,** 761-780 (2013).

14. Harrison, P. A. *et al.* Cross-sectoral impacts of climate change and socio-economic change for multiple European land- and water-based sectors. *Clim. Chang.* **128,** 279-292 (2015).

15. Mokrech, M., Kebede, A. S., Nicholls, R. J., Wimmer, F., Feyen, L. An integrated approach for assessing flood impacts due to future climate and socio-economic conditions and the scope of adaptation in Europe. *Clim. Chang.* **128,** 245-260 (2015).

16. Dunford, R., Smith, A., Harrison, P. A., Hangau, D. Ecosystem service provision in a changing Europe: adapting to the impacts of combined climate and socio-economic change. *Landscape Ecology* **30,** 443-461 (2015).

17. Dunford, R., Harrison, P. A., Jäger, J., Rounsevell, M. D. A., Tinch, R. Exploring climate change

vulnerability across sectors and scenarios using indicators of impacts and coping capacity. *Clim. Chang.* **128,** 339-354 (2015).

18. Jäger, J. *et al.* Assessing policy robustness of climate change adaptation measures across sectors and scenarios. *Clim. Chang.* **128,** 395-407 (2015).
19. Kebede, A. S. et al. The sensitivity of cross-sectoral impacts to climate and socio-economic drivers for key European sectors. *Clim. Chang.* **128,** 261-277 (2015).
20. Dunford, R., Harrison, P. A., Rounsevell, M. D. A. Exploring scenario and model uncertainty in cross-sectoral integrated assessment approaches to climate change impacts. *Clim. Chang.* **132,** 417-432 (2014).
21. Brown, C. *et al.* Analysing uncertainties in climate change impact assessment across sectors and scenarios. *Clim. Chang.* **128,** 293-306 (2015).
22. Nakićenović, N. *et al. Special Report on Emissions Scenarios.* (Cambridge Univ. Press, 2000).
23. Dubrovsky, M., Trnka, M., Holman, I. P., Svobodova, E., Harrison, P. A. Developing a reduced-form ensemble of climate change scenarios for Europe and its application to selected impact indicators. *Clim. Chang.* **128,** 169-186 (2015).
24. Busch, G. Future European agricultural landscapes – what can we learn from existing quantitative land use scenario studies? *Agric. Ecosyst. Environ.* **114,** 121-140 (2006).
25. Arnell, N. W. *et al.* A global assessment of the effects of climate policy on the impacts of climate change, *Nat. Clim. Chang.* **3**, 512-519 (2013).

Author to whom correspondence and requests for materials should be addressed is Paula A. Harrison, email: PaulaHarrison@ceh.ac.uk

Acknowledgements

The research leading to these results has received funding from the European Commission Seventh Framework Programme under Grant Agreement No. 244031 (The CLIMSAVE Project; Climate change integrated assessment methodology for cross-sectoral adaptation and vulnerability in Europe; www.climsave.eu); and No. 603416 (The IMPRESSIONS project; Impacts and risks from higher-end scenarios: strategies for innovative solutions). The authors wish to thank all the modellers that contributed towards the development of the IAP in these projects.

Author Contributions

PAH conceived the idea for the study; all authors designed the study; RWD undertook the model runs and data analysis; all authors contributed towards the writing of the paper.

Competing Financial Interests statement

The authors declare no competing financial interests

Figure Legends

Figure 1: Comparison of single sector and integrated model outcomes: proportion of dataset where identical values are found between the single sector and integrated models. Black squares reflect the range (R) of data: ■ = R>5%,■■ = R>15%, ■■■ = R>30%.

Figure 2: Difference due to (a) under-estimation and (b) over-estimation of single sector models compared to integrated models. The values are based on the total of all positive (a) or negative (b) differences summed across all grid cells and standardised relative to the baseline value.

Figure 3: Spatial patterns in differences between single sector and integrated models for an indicative scenario (GFCM21 climate model combined with SRES A2 emissions and socio-economic changes). Both positive and negative differences are presented relative to baseline levels at the grid-cell scale.

Figure 4: Differences between single sector and integrated model impact indicators for the five European regions used in the Europe Chapter of the IPCC AR5[1]. Positive differences indicate that the integrated model produces higher values than single sector models; negative differences indicate that the single sector model values are greater. Both positive and negative differences are presented relative to baseline levels at the regional scale. Based on the GFCM21 climate model combined with baseline or future socio-economics.

Figure 5: Differences between single sector and integrated models by region with respect to the minimum and maximum European summed IAP results for each indicator. Colour indicates the agreement between model types in terms of the direction of change; triangle and arrow symbols indicate the magnitude of difference between the single sector and integrated models. All units are % change from baseline ($\%_{BL}$): a value that changes from 100% to 75% of baseline would be $-25\%_{BL}$.

Online-only Methods Section

Climate change impact modelling needs to include cross-sectoral interactions

Paula A. Harrison, Robert W. Dunford, Ian P. Holman and Mark D.A. Rounsevell

The CLIMSAVE IAP

The CLIMSAVE[1] IAP[12,13] integrates a suite of sectoral models, including agriculture, forests, biodiversity, flooding, water resources and urban development to simulate the cross-sectoral effects of different climate and socio-economic scenarios across Europe. To facilitate the cross-sectoral model linkages and to reduce model run-time within the web-based software environment, a meta-modelling approach was used whereby computationally efficient or reduced-form models that emulate the performance of more complex models were developed (see Supplementary Table 1 for further details). Each meta-model has been calibrated and validated against either historical observations or the outputs from the validated complex models – see citations within Supplementary Table 1. In addition, all of the meta-models have undergone comprehensive sensitivity analysis[19] and uncertainty analysis[20,21] and been reported within integrated cross-sectoral impact, adaptation and vulnerability assessments[4,14,17].

The IAP is based on a web Client / Server architecture that uses both server-based (i.e. remote) and client-based (i.e. the user's PC) computing solutions on the web[13,26]. The models are hard-linked (i.e. there is no off-line coupling) within the server-side software environment. Supplementary Figure 2 schematically illustrates the model inter-linkages showing the key model variables that are passed between models. The interactions take place as part of a hierarchical model chain. The exception is

[1] CLimate change Integrated Methodology for cross-Sectoral Adaptation and Vulnerability in Europe

for the interaction between agriculture and water availability for irrigation, whereby the maximum allowed water withdrawals for irrigation (from the Water Availability model) constrains the Rural Land Allocation model, the results from which determine the actual irrigation water use which then feeds into the Water Use model and the assessment of overall water exploitation. This approach was chosen to keep runtime to a minimum within the web-based system. However, within the broader concept of the IAP, the user of the IAP provides the feedback mechanism, as undesirable impacts in a 'downstream' sector (for example, on habitats) can be used to trigger changes in the input values for earlier models within the following model run.

As an example of these inter-linkages, the Rural Land Allocation Model optimises the spatial rural land allocation to meet scenario food demand by selecting between intensive agriculture (arable or dairying), extensive agriculture (grass-based livestock systems), managed forest, unmanaged forest or unmanaged land based on profit maximisation under a range of constraints. Land use selection is constrained by land that is unavailable for agricultural use due to urbanisation (from the Urban Model), frequency of flooding (from the Flooding Model), protected area status or physical constraints (e.g. soil depth). Crops are selected on the basis of relative profitability, which depends on their simulated rainfed and irrigated yields (from the Crop Yield Model) and the maximum allowed water withdrawals for irrigation in a given river basin (from the Water Availability Model). Managed versus unmanaged forest is determined on the basis of whether simulated timber yields (from the Forestry Model) for the baseline tree species achieve sufficient profit. Capital, people and trade flows are treated exogenously within the IAP, so that GDP, population and food imports are specified as scenario variables. Crop and livestock production prices are not set but are iteratively adjusted within each IAP run so that farm profits allow sufficient agricultural area to meet the required European food demand. As European food demand increases, imports decrease and/or agri-environment measures (such as buffer strips, set-aside, etc.) increase, then simulated food prices will increase. Outputs of simulated irrigation usage and habitat availability are passed from the Rural Land Allocation to the Water Use and Biodiversity models, respectively.

The Platform operates at a spatial resolution of 10 arcmin x 10 arcmin (approximately 16km x 16km in Europe) for all Member States of the European Union minus Croatia (EU27) plus Norway and Switzerland. The IAP runs for three independent thirty year time slices: baseline (1961-90 climate with 2010 socio-economics), 2020s and 2050s. Hence, there is no time-dependence in the model runs. It produces outputs of both sector-based impact indicators and ecosystem services (see examples in Supplementary Table 1) taking account of cross-sectoral trade-offs in order to link climate change impacts directly to human well-being. Fourteen impact indicators were selected to cover different sectors/ecosystem services for the comparison of single sector vs integrated model runs: food provision, area of arable land (including set-aside), area of intensive agriculture, area of extensive grassland, area of managed forest, area of unmanaged forest, area of unmanaged land, carbon storage, water exploitation index, irrigation use, number of people flooded (1% annual probability), arable biodiversity, forest biodiversity and urban land area (see Supplementary Table 4 for further details).

Scenario experiments

The IAP was run for 41 scenario experiments for the 2050s to explore how uncertainties arising from climate and socio-economic change affect the differences between the single sector and integrated model runs. These scenario experiments included:

- one baseline scenario using current socio-economic conditions (2010) and climate data (1961-1990 average);

- 20 climate change-only scenarios based on four SRES emissions scenarios (A1, A2, B1, B2)[22] combined with five climate models (MPEH5, CSMK3, HadGEM, GFCM21 and IPCM4) selected to represent as much uncertainty as possible arising from between-GCM differences[21]. Projections of Europe-wide average temperature change range from 1.5 to 4^{o}C in the 2050s, whilst precipitation changes range from increases of between 1 and 11% in winter and decreases of between 4 and 25% in summer;
- 20 combined climate and socio-economic scenarios where socio-economic conditions are changed from baseline based on the same four SRES scenario storylines, downscaled to Europe using information from previous studies [27,28] and expert opinion (see Supplementary Table 3 for details of the quantified values used for different socio-economic inputs to the IAP).

Both the single sector and integrated models were run for the climate change scenarios alone and for combined climate and socio-economic scenarios to determine the differences due to different drivers of change.

The climate and socio-economic scenarios were applied separately as well as combined to tease apart the roles that the different drivers play in single sector and integrated model outcomes. The climate change scenarios were run with baseline socio-economics (rather than simulating future 2050s socio-economics with baseline climate) to be consistent with current understanding of climate change. Our focus therefore allows us to understand how the inclusion of socio-economic changes modifies the impacts associated with climate change.

Statistical analysis

Grid cell differences between single sector and integrated models were calculated by subtracting the two variables from one another. The number of cells with a difference value greater than zero was calculated and used for Figure 1 in the main article. Statistical similarity in the spatial distribution of the impact indicators between the single sector and integrated models has been assessed using the concordance coefficient (Supplementary Figure 3). Concordance metrics were calculated by applying Lin's equation[29] to the single sector and integrated datasets for a given scenario experiment providing a measure which reflects the goodness of fit to a 1:1 line. Those indicators heavily influenced by the inputs of other models, reflecting cross-sectoral interactions, generally show lower concordance: food provision, water exploitation, carbon storage, irrigation and extensive grassland all show notable differences (concordance correlation coefficient, $pc < 0.95$) under at least one scenario combination. Concordance values vary between climate models reflecting the influence of the different spatial patterns of temperature and precipitation change. The socio-economic scenarios introduce further significant spatial differences between the single sector and integrated models when compared with differences for the same climate model under current socio-economic conditions.

The total difference between single sector and integrated models was calculated for each scenario pair and the total over-estimation (positive difference) and under-estimation (negative difference) calculated by summing all difference values greater than and less than zero, respectively. These differences were then standardised by re-calculating them as the proportion of the total value for the same indicator from the baseline scenario experiment (Figure 2 in main article). A regional analysis of the differences was performed in a similar manner by calculating total differences for each IPCC region and standardising them relative to the total value for the region for the same indicator from the baseline scenario experiment (Figure 4 in the main article).

The total value and change from baseline were calculated for each indicator and scenario experiment for the whole of Europe and each of the five IPCC European regions (Supplementary Figure 4) for both the single sector and integrated model runs. The maximum and minimum extreme values of each indicator for each scale were identified from the totals and standardised by calculating each as a proportion of the baseline value (Figure 5 in main article). Direction relative to baseline was identified using this proportional value; if the value was greater than or equal to 101% of baseline it was classified as an increase, and if less than or equal to 99% of baseline classified as a decrease. Direction was compared between the single sector and integrated models, and each indicator was classified in terms of whether the directions were different or the same, and if so, in which direction. The range was calculated for each indicator at each spatial scale by subtracting the minimum indicator value (as a proportion of baseline) of any scenario from the equivalent maximum. This was performed for both the single sector and integrated models and the difference in range resulting from model integration was calculated by subtracting the single sector range from the integrated range. The scenario with the highest value and the scenario with the lowest value, compared to baseline, was also computed for each of the five IPCC regions and compared for the single sector and integrated models for the IPCC indicators given in Table 1 (main article) (see Supplementary Table 5). This provides an overview of how results in the IPCC Europe chapter might differ from what has been reported if the studies had taken account of cross-sectoral interactions.

References for the Online Methods Section

26. Holman, I., Cojocaru, G. Report describing the Integrated Assessment Platform (IAP) specification, meta-model specifications and the multi-scale approach. Available from www.climsave.eu (accessed 09/03/16) (2011).

27. Rounsevell, M.D.A. *et al.* A coherent set of future land use change scenarios for Europe. *Agric. Ecosyst. Environ.* **114,** 57-68 (2006).

28. Abildtrup, J. *et al.* Socio-economic scenario development for the assessment of climate change impacts on agricultural land use: a pairwise comparison approach *Environ. Sci. Policy* **9,** 101-115 (2006).

29. Lin, L.I.K. A concordance correlation coefficient to evaluate reproducibility. *Biometrics* **45,** 255-268 (1989).

Figure 1: Comparison of single sector and integrated model outcomes: proportion of dataset where identical values are found between the single sector and integrated models. Black squares reflect the range (R) of data: ■ = R>5%,■■ = R>15%, ■■■ = R>30%.

Socio-economic scenario	Baseline					
Climate model	IPCM4	CSMK3	HadGEM	GFCM21	MPEH5	
Emission scenario	A2					
Food provision	23%	28%	20%	20%	25%	■
Water exploitation index	24%	24%	21%	26%	22%	
Arable land	39%	39%	37%	39%	38%	
Carbon storage	52%	55%	56%	52%	54%	
Irrigation	69%	68%	63%	64%	68%	■
Biodiversity (arable)	77%	79%	78%	80%	77%	
Unmanaged land	83%	78%	82%	84%	70%	■
Intensive agriculture	89%	88%	87%	80%	81%	■
Flooded people	89%	91%	88%	88%	89%	
Extensive grassland	93%	90%	91%	89%	81%	■
Managed forest	94%	92%	92%	91%	92%	
Biodiversity (forest)	91%	90%	93%	95%	91%	
Unmanaged forest	98%	97%	97%	97%	96%	
Urban area	100%	100%	100%	100%	100%	

Socio-economic scenario	Baseline				
Climate model	GFCM21				
Emission scenario	A1	A2	B1	B2	
Food provision	21%	20%	18%	19%	
Water exploitation index	26%	26%	29%	29%	
Arable land	43%	39%	39%	38%	
Carbon storage	54%	52%	51%	52%	
Irrigation	66%	64%	71%	69%	■
Biodiversity (arable)	79%	80%	82%	82%	
Unmanaged land	85%	84%	72%	77%	■
Intensive agriculture	82%	80%	81%	81%	
Flooded people	88%	88%	88%	88%	
Extensive grassland	89%	89%	79%	82%	■
Managed forest	93%	91%	93%	93%	
Biodiversity (forest)	94%	95%	95%	95%	
Unmanaged forest	98%	97%	97%	97%	
Urban area	100%	100%	100%	100%	

Socio-economic scenario	A1	A2	B1	B2	
Climate model	GFCM21				
Emission scenario	A1	A2	B1	B2	
Food provision	47%	5%	26%	3%	■■■
Water exploitation index	28%	28%	23%	26%	
Arable land	59%	28%	44%	26%	■■■
Carbon storage	54%	61%	48%	47%	■
Irrigation	70%	51%	54%	55%	■■
Biodiversity (arable)	62%	84%	76%	85%	■■
Unmanaged land	37%	51%	38%	76%	■■■
Intensive agriculture	63%	41%	52%	73%	■■■
Flooded people	82%	76%	82%	88%	■
Extensive grassland	83%	71%	76%	80%	■
Managed forest	69%	85%	69%	91%	■■
Biodiversity (forest)	89%	90%	96%	93%	■
Unmanaged forest	92%	94%	89%	96%	■
Urban area	100%	100%	100%	100%	

Socio-economic scenario	A2					
Climate model	IPCM4	CSMK3	HadGEM	GFCM21	MPEH5	
Emission scenario	A2					
Food provision	6%	7%	6%	5%	7%	
Water exploitation index	31%	29%	29%	28%	28%	
Arable land	28%	29%	27%	28%	29%	
Carbon storage	51%	47%	54%	61%	59%	■
Irrigation	81%	81%	78%	51%	63%	■■■
Biodiversity (arable)	85%	86%	86%	84%	85%	
Unmanaged land	50%	51%	51%	51%	51%	
Intensive agriculture	46%	46%	44%	41%	46%	
Flooded people	76%	76%	76%	76%	76%	
Extensive grassland	66%	67%	70%	71%	71%	
Managed forest	80%	79%	82%	85%	84%	■
Biodiversity (forest)	93%	94%	93%	90%	91%	
Unmanaged forest	92%	91%	91%	94%	93%	
Urban area	100%	100%	100%	100%	100%	

Keys:

Scale
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%

Range	
<5%	
5-10%	■
10-25%	■■
>25%	■■■

Figure 2: Difference due to (a) under-estimation and (b) over-estimation of single sector models compared to integrated models. The values are based on the total of all positive (a) or negative (b) differences summed across all grid cells and standardised relative to the baseline value.

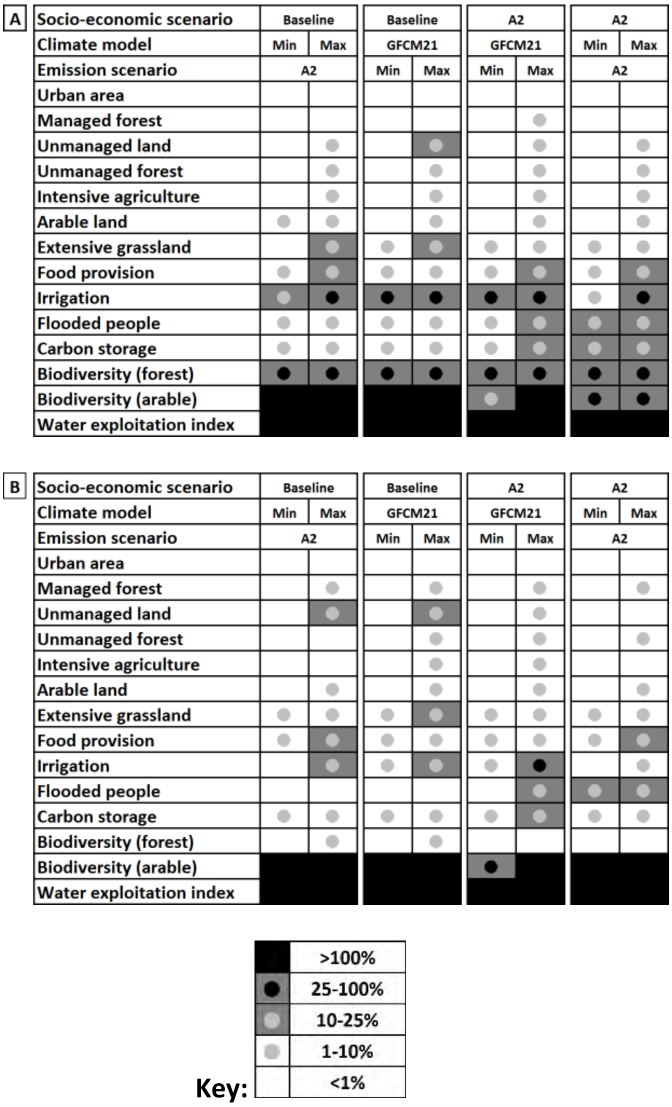
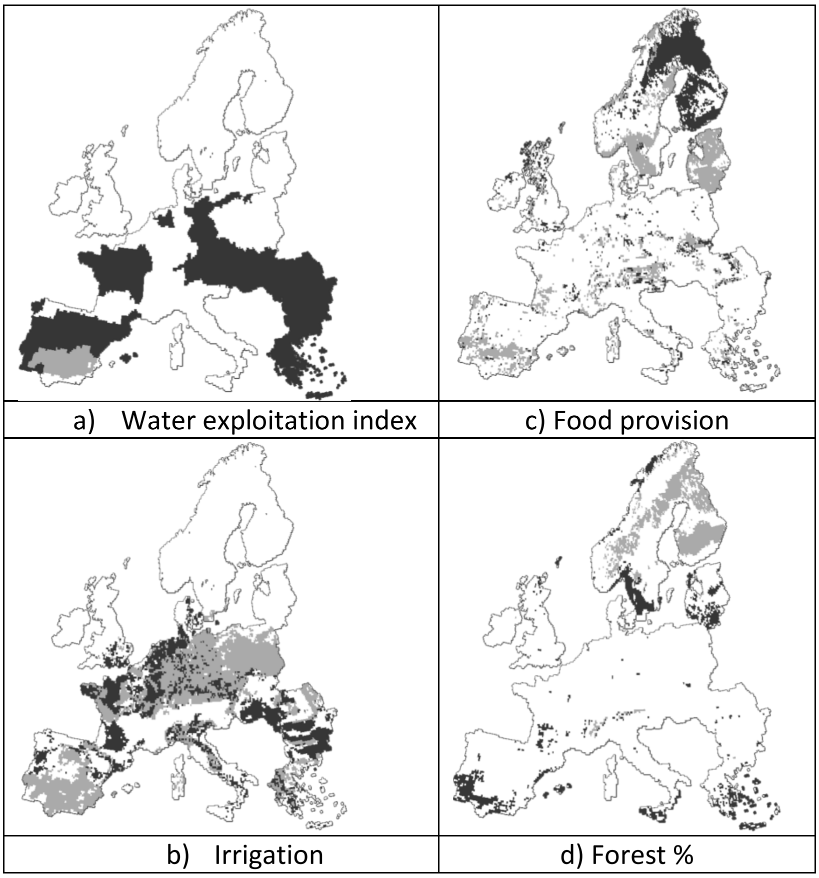


Figure 3: Spatial patterns in differences between single sector and integrated models for an indicative scenario (GFCM21 climate model combined with SRES A2 emissions and socio-economic changes). Both positive and negative differences are presented relative to baseline levels at the grid-cell scale.



difference integrated > single sector > 25%		25% > difference > -25%		difference integrated < single sector <-25%	

Figure 4: Differences between single sector and integrated model impact indicators for the five European regions used in the Europe Chapter of the IPCC AR5[1]. Positive differences indicate that the integrated model produces higher values than single sector models; negative differences indicate that the single sector model values are greater. Both positive and negative differences are presented relative to baseline levels at the regional scale. Based on the GFCM21 climate model combined with baseline or future socio-economics.

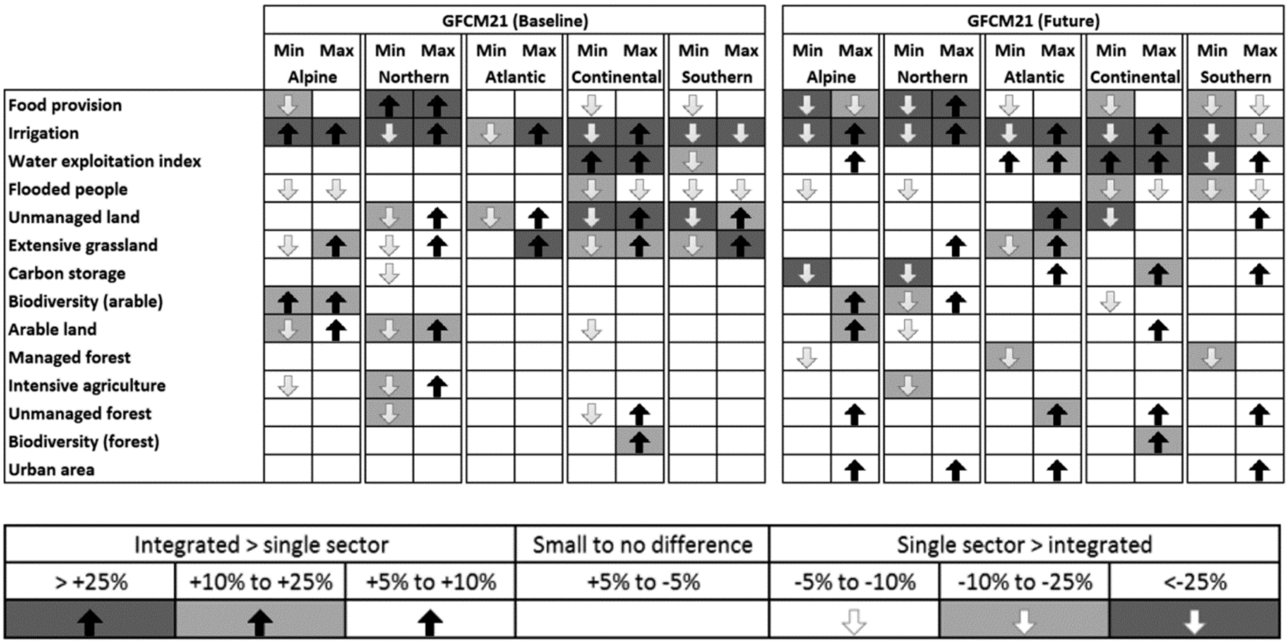


Figure 5: Differences between single sector and integrated models by region with respect to the minimum and maximum European summed IAP results for each indicator. Colour indicates the agreement between model types in terms of the direction of change; triangle and arrow symbols indicate the magnitude of difference between the single sector and integrated models. All units are % change from baseline ($\%_{BL}$): a value that changes from 100% to 75% of baseline would be $-25\%_{BL}$.

	Difference Integrated - Standalone																	
	MINIMUM						MAXIMUM						CHANGE IN RANGE					
	EUROPE	Alpine	Atlantic	Continental	Northern	Southern	EUROPE	Alpine	Atlantic	Continental	Northern	Southern	EUROPE	Alpine	Atlantic	Continental	Northern	Southern
Biodiversity (arable)	▼▼	▲▲	▼▼	▼▼	▼▼	▼▼	▼	▼	▼	▼▼	▼▼	▼▼	↑↑	↓↓↓	↑↑↑	↑↑		
Unmanaged land	▲	▲	▲	▲▲	▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	↑↑↑	↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑↑
Biodiversity (forest)	▼▼		▼▼	▼▼	▼▼	▼▼	▽	▽	▼	▼▼	▼	▲▲	↑↑	↓↓	↑↑		↑↑↑	↑↑↑
Arable land	▲	△	△	△		▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	↑↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑
Intensive agriculture	△	△	△	△		▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑	↑↑
Extensive grassland	△		▲▲	△			▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	↑↑	↑↑↑	↑↑↑	↑↑↑	↑↑	↑↑↑
Irrigation		▲▲	△				▲	▲▲	▼▼	▲▲	▲▲	▽	↑↑	↑↑↑	↓↓↓	↑↑↑	↑↑↑	↓
Carbon storage				▲		▼▼	▽	▼▼		▲▲	▼	▼▼		↓↓↓			↓↓	↓↓
Water exploitation index	△			△		▲	▲		△	▲▲		▲			↑	↑↑↑		
Food provision		▽		▽	▲▲					▽				↑			↓↓↓	
Flooded people				▽		▽		△				▽		↑				
Unmanaged forest					▽						▽							
Urban area																		
Managed forest																		

Direction of change from baseline: do single sector and integrated models agree?			
(■) Single sector and integrated show opposing directions	(■) Single sector and integrated both negative	(■) Single sector and integrated both positive	(☐) No change in Single sector or integrated
Amount of difference as a result of integration: calculated as integrated (I) minus single sector (S) so positive values are where I>S			
Increase (▲ or △) or Decrease (▽ or ▼)	Change >50% (▲▲ or ▼▼)	Change > 25% (▲ or ▼)	Change > 10% (△ or ▽)
Change in range as a result of integration:			
Range is expanding (↑) or contracting (↓)	Change >50% (↑↑↑ or ↓↓↓)	Change > 25% (↑↑ or ↓↓)	Change > 10% (↑ or ↓)

Climate change impact modelling needs to include cross-sectoral interactions

Paula A. Harrison, Robert W. Dunford, Ian P. Holman and Mark D.A. Rounsevell

Supplementary Table 1: Details of the meta-models included within the CLIMSAVE IAP (adapted from reference 13 in main text).

Sector	Original model	Meta-model	Meta-modelling approach	Example output indicators
Urban	Regional Urban Growth (RUG)[30]	Meta-RUG[26]	Look-up tables	Percent Artificial surfaces
Snow	SnowMAUS snow cover simulator[31]	Meta-SnowCover[23]	Artificial neural networks	Skiing days
Agriculture (crop yields)	ROIMPEL[32]	Meta-Crop yield (winter wheat and spring wheat, winter barley and spring barley, winter oil seed rape, potatoes, grain maize, sunflower, soybean, cotton, grass, olives)[2]	Soil/climate clustering combined with artificial neural networks	Average yield (irrigated and rainfed) Irrigation need (mm)
Forestry	GOTILWA+ [33]	Meta-GOTILWA+ [2]	Artificial neural networks	Potential wood yield Potential Net Ecosystem Exchange
Rural land allocation	SFARMOD[34,35]	Meta-SFARMOD[2]	Soil/climate clustering combined with multiple regression	Percent intensive/extensive/forest/unmanaged Crop areas Irrigation usage
Water resources and demand	Water - Global Assessment and Prognosis (WaterGAP3)[36]	WaterGAP meta-model (WGMM)[6]	3-dimensional surface response diagrams	Water availability Median annual flood discharge Total water use Water Exploitation Index
Flooding	RegIS2[37] and DIVA[38]	Coastal Fluvial Flood meta-model (CFFlood)[15]	Simplified process-based model	People flooded Damages due to flooding
Pests	CLIMEX[39]	Meta-pest[23]	Artificial neural networks	Number of generations
Biodiversity (species)	SPECIES[40]	SPECIES[40,26]	Artificial neural networks	Potential climate suitability Potential climate and habitat suitability
Biodiversity (ecosystems)	LPJ-GUESS[41]	Meta-LPJ-GUESS[42]	Look-up tables	Net Primary Production Biomass

Benchmarking the IAP against the "Europe" chapter of the IPCC AR5

The outcomes from running the single sector models within the IAP in stand-alone (i.e. without coupling) mode are qualitatively compared with the findings from the IPCC[1] (which represent a wide range of single sector studies) in Supplementary Table 2, demonstrating broad similarity given the differences in spatial/temporal scales, indicator definitions and scenarios (climate and socio-economic). This supports the comparison of the single sector and integrated model runs by showing that the differences between the modelling approaches can be attributed to the effect of cross-sectoral integration rather than the performance of the models *per se*.

According to the IPCC, urban development is projected to increase, which corresponds with increases in urban areas of 5-9% in the IAP. Water availability decreases at the European scale and for the southern, continental and Atlantic regions in the IAP, consistent with IPCC statements on water availability and water restrictions. Irrigation needs and the number of people flooded are reported to increase in the IPCC, broadly in line with the IAP, but the IAP projects a wider potential range of both increases and decreases in irrigation needs. IPCC indicators related to agriculture (cereal yield, grassland, food production) decrease in general in all regions except northern Europe, broadly consistent with the IAP, but with the IAP again covering a wider range of changes, particularly for food production, depending on the socio-economic scenario. Indicators associated with forests (timber yield, forest area and carbon sequestration) agree at the European scale and for some regions (e.g. southern), but differ in other regions (e.g. Atlantic). Finally, the IPCC suggests a predominant declining trend in biodiversity in all areas except northern Europe with increased species vulnerability and habitat loss. This corresponds with the IAP except for the Alpine region which shows the potential for both increases and decreases depending on the scenario.

Supplementary Table 2: Comparison of climate change impacts in Europe from the IPCC AR5 with trends from running the IAP as single sector models. Arrows in the left-hand side of the table are used to reflect an interpretation of the IPCC report: ↑ increase; ↕ mixed trends; ↓ decrease (empty cells reflect no information). Arrows in the right-hand side of the table are used to summarise maximum (top icon) and minimum (bottom icon) IAP results from all scenarios explored: ⬆ positive >= +10% of baseline; ▪ between ± 10% of baseline; ⬇ negative >= -10% of baseline.

IPCC Indicator	EUROPE	Alpine	Atlantic	Continental	Northern	Southern	IAP indicator	EUROPE	Alpine	Atlantic	Continental	Northern	Southern
Urban development	↑			↑			Urban area (km^2)	▪ ▪	▪ ▪	▪ ▪	▪ ▪	▪ ▪	▪ ▪
Water availability	↓						Water availability (mill. $m^3 yr^{-1}$)	▪ ⬇	⬆ ▪	▪ ⬇	▪ ⬇	⬆ ▪	⬇ ⬇
Water restrictions	↑		↑	↑		↑							
Irrigation needs	↑						Irrigation (mill. $m^3 yr^{-1}$)	⬆ ⬇	⬆ ⬆	⬆ ⬇	⬆ ⬆	⬆ ⬇	⬆ ⬇
People affected by flooding	↑		↑	↑	↑	↑	Flooded people (people)	⬆ ⬆	⬆ ▪	⬆ ⬆	⬆ ▪	⬆ ▪	⬆ ⬆
Grassland production	↓		↓				Extensive Grassland (km^2)	⬇ ⬇	▪ ⬇	⬆ ⬇	⬇ ⬇	▪ ⬇	⬇ ⬇
Cereal yields	↓		↓	↓	↑	↓	Food Provision (PJ)	⬆ ⬇	⬆ ⬇	⬆ ⬇	⬆ ⬇	⬆ ⬇	⬆ ⬇
Food production	↓	↓	↓	↓	↕	↓							
Carbon sequestration (forests)	↑	↕	↑	↑	↑	↑	Total Carbon Storage (Gt Carbon)	⬆ ▪	⬆ ⬇	▪ ⬇	⬇ ⬇	⬆ ▪	⬆ ⬆
Forest growth/ timber/ wood production	↕	↕	↑	↓	↑	↓	Wood yield (t $ha^{-1} yr^{-1}$)	⬆ ⬇	⬆ ⬇	▪ ⬇	⬆ ⬇	⬆ ⬇	⬇ ⬇
Forest land area	↑						Overall forest area(km^2)	⬇ ⬇	⬇ ⬇	⬇ ⬇	⬇ ⬇	⬇ ⬇	⬇ ⬇
							Unmanaged Land (km^2)	⬆ ⬇	▪ ⬇	⬆ ⬇	⬆ ⬇	⬆ ⬇	⬆ ⬇
Biodiversity (predominant trend)	↓	↓	↓	↓	↑	↓	Biodiversity based on suitable climate space (species/km^2)	▪ ⬇	⬆ ⬇	▪ ⬇	▪ ⬇	⬆ ▪	⬇ ⬇

Supplementary Table 3: Quantification of socio-economic and climate drivers for the 2050s for the IAP based on the SRES storylines.

Indicator	**SRES A1**	**SRES A2**	**SRES B1**	**SRES B2**
SOCIAL DRIVERS				
Population change (% from current)	5	25	5	0
Water savings due to behavioural change (% from current)	-30	-5	40	50
Change in dietary preferences for beef and lamb (% from current)	20	5	-5	-20
Change in dietary preferences for chicken and pork (% from current)	10	0	-5	-20
Household externalities preference	1 (rural)	3	4	5 (urban)
TECHNOLOGICAL DRIVERS				
Change in agricultural mechanisation (% from current)	75	5	40	10
Water savings due to technological change (% from current)	45	0	35	10
Change in agricultural yields (% from current)	50	10	25	-10
Change in irrigation efficiency (% from current)	60	5	40	10
ECONOMIC DRIVERS				
GDP change (% from current)	50	5	25	10
Oil Price (% from current)	80	300	180	200
Change in bioenergy production (% from current)	5	5	15	25
Change in food imports (% from current)	20	-10	10	-15
ENVIRONMENTAL DRIVERS				
Set-aside (%)	0	0	10	5
Reducing diffuse source pollution from agriculture (ratio)	0.8	0.8	1.2	1.1
POLICY DRIVERS				
Compact (C) vs sprawled (S) urban development	Low (S)	Med	High (C)	High (C)
Attractiveness of the coast for urban development	High	Med	Low	Low
CLIMATE DRIVERS				
Area-average summer temperature change (^{o}C)[1]	2.2 to 2.9	2.1 to 2.8	1.6 to 2.2	1.9 to 2.5
Area-average winter temperature change (^{o}C)[1]	2.4 to 3.8	2.3 to 3.7	1.8 to 2.9	2.0 to 3.3
Area-average summer precipitation change (%)[1]	-24.5 to -5.3	-23.4 to -5.2	-20.2 to -4.3	-21.5 to -4.7
Area-average winter precipitation change (%)[1]	1.5 to 10.5	1.5 to 10.1	1.1 to 7.8	1.3 to 8.9
Sea level rise (cm)	20.7	19.2	18.2	18.9

[1] Range over the five climate models (MPEH5, CSMK3, HadGEM, GFCM21 and IPCM4) per SRES emissions scenario. Summer defined as June, July, August. Winter defined as December, January, February.

Supplementary Table 4: Description of the 14 indicators used in the analysis.

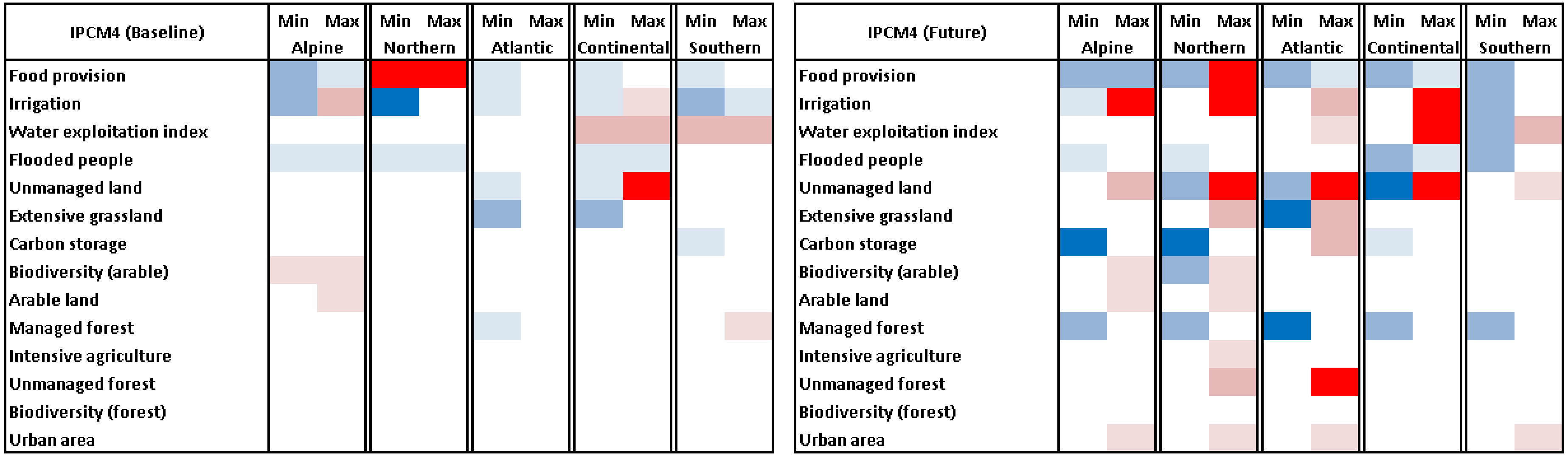
Indicator	Description
Food production (PJ)	Gridded production-weighted food production derived as total daily calories of all foodstuffs modelled for each grid cell divided by the population.
Arable land (km^2)	Area of each grid cell under arable crops.
Intensive agriculture (km^2)	Area of each grid cell under arable or dairying.
Extensive agriculture (km^2)	Area of each grid cell under sheep and beef cattle farming.
Irrigation (mill. m^3 yr^{-1})	Average annual volume of irrigation usage.
Water Exploitation Index (units)	Proportion of the available water resources in each catchment that is abstracted for agricultural, domestic or energy production.
People flooded (number of people)	The number of people flooded by coastal and/or fluvial flooding in a 1 in 100 year (1%) event.
Managed forest (km^2)	Area of each grid cell under managed forest.
Unmanaged forest (km^2)	Area of each grid cell under unmanaged forest.
Carbon storage (Gt Carbon)	Potential carbon stock.
Forest biodiversity (index)	A measure of the total number of species associated with forest habitats within each grid cell that lose or gain both suitable climate and habitat space.
Arable biodiversity (index)	A measure of the total number of species associated with arable habitats within each grid cell that lose or gain both suitable climate and habitat space.
Unmanaged land (km^2)	Area of each grid cell that is not under agricultural, forestry or urban land uses.
Urban area (km^2)	Area of each grid cell under urban/suburban land cover.

Supplementary Table 5: Comparison of IAP indicators from Supplementary Table 2 for single sector and integrated models relative to baseline values. Top icon based on the scenario with the highest value compared to baseline; bottom icon based on the scenario with the lowest value compared to baseline.

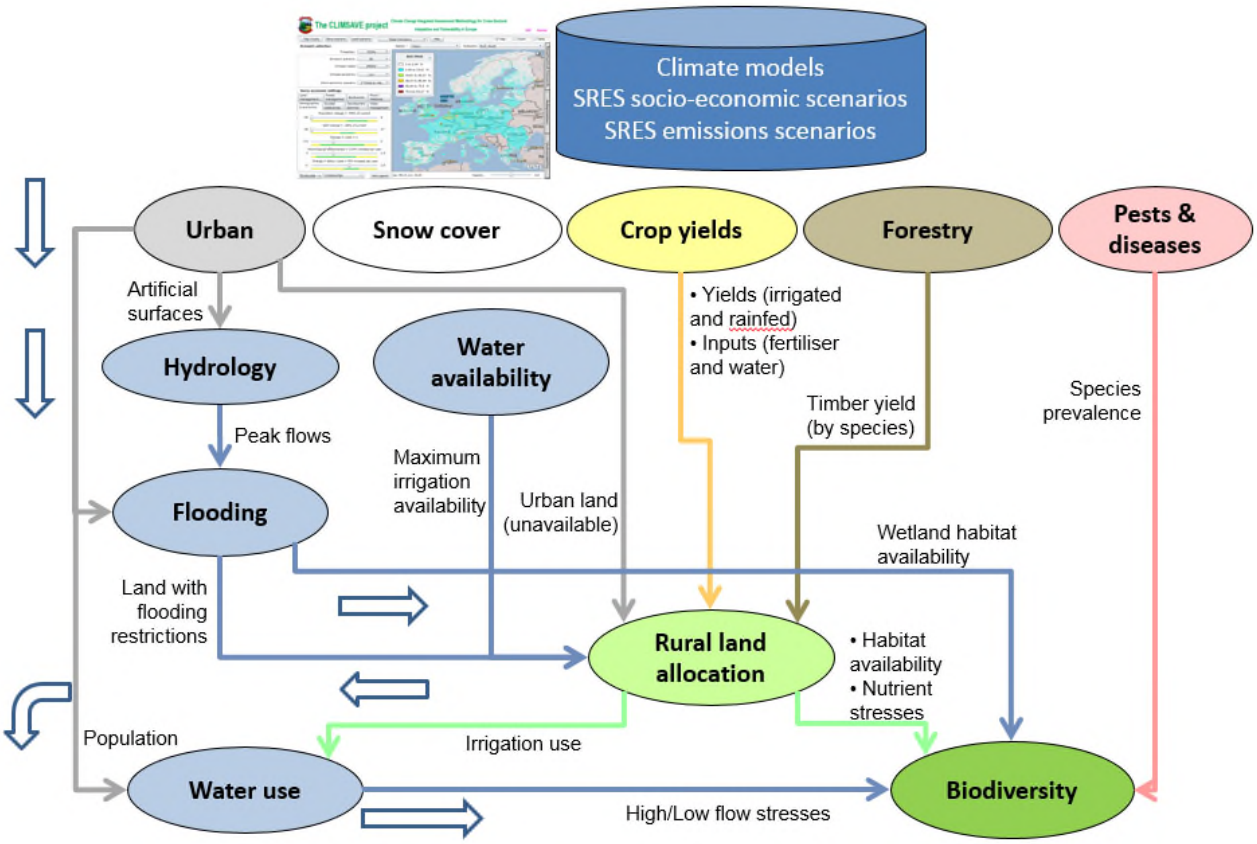
	SINGLE SECTOR							INTEGRATED					
	EUROPE	Alpine	Atlantic	Continental	Northern	Southern		EUROPE	Alpine	Atlantic	Continental	Northern	Southern
Urban area (km^2)	▪ ▪	▪ ▪	▪ ▪	▪ ▪	▪ ▪	▪ ▪		▪ ▪	▪ ▪	▪ ▪	▪ ▪	▪ ▪	▪ ▪
Water availability (mill. $m^3\ yr^{-1}$)	▪ ▽	△ ▪	▪ ▽	▪ ▽	△ ▪	▽ ▽		▪ ▽	△ ▪	△ ▽	▽ ▼	▪ ▪	▼ ▼
Irrigation (mill. $m^3\ yr^{-1}$)	▲ ▽	▲ △	▲ ▼	▲ △	▲ ▼	▲ ▽		▲ ▽	▲ ▲	▲ ▼	▲ △	▲ ▼	▲ ▽
People flooded (people)	△ △	△ ▪	▲ △	△ ▪	△ ▪	△ △		△ ▪	△ ▪	▲ △	△ ▪	△ ▪	△ ▪
Arable land (excluding set-aside; km^2)	▽ ▼	▲ ▼	▽ ▼	▽ ▼	▲ ▼	▽ ▼		▲ ▽	▲ ▼	△ ▼	▲ ▼	▲ ▼	△ ▽
Intensive agriculture (km^2)	▽ ▼	▪ ▼	▽ ▼	▽ ▼	▲ ▼	▼ ▼		△ ▼	▲ ▼	△ ▼	△ ▼	▲ ▼	△ ▼
Extensive grassland (km^2)	▽ ▼	▪ ▼	▲ ▽	▽ ▼	▪ ▼	▽ ▼		△ ▼	▲ ▼	▲ ▲	▲ ▼	▲ ▼	△ ▼
Food provision (PJ)	△ ▽	▲ ▽	△ ▽	▲ ▽	▲ ▼	△ ▽		△ ▽	▲ ▽	△ ▽	▲ ▽	▲ ▽	△ ▽
Carbon storage (Gt Carbon)	△ ▪	▲ ▽	▪ ▽	▽ ▽	△ ▪	▲ ▲		△ ▽	△ ▽	▪ ▽	△ ▪	▪ ▽	△ ▪
Wood yield ($t\ ha^{-1}\ yr^{-1}$)	▲ ▼	▲ ▼	▪ ▼	▲ ▼	▲ ▼	▽ ▼		▲ ▽	▲ ▽	△ ▼	▲ ▼	▲ △	▽ ▼
Overall forest area (km^2)	▼ ▼	▼ ▼	▼ ▼	▼ ▼	▽ ▼	▼ ▼		▽ ▽	▪ ▽	▽ ▼	▽ ▼	▪ ▼	▽ ▼
Unmanaged land (km^2)	▲ ▽	▪ ▽	▲ ▽	▲ ▼	▲ ▽	△ ▼		▲ ▪	▲ ▽	▲ ▪	▲ ▪	▲ ▪	▲ ▪
Biodiversity based on climate space (species/km^2)	▪ ▽	△ ▽	▪ ▽	▪ ▽	▲ ▪	▽ ▽		▪ ▽	△ ▪	▪ ▽	▪ ▽	▲ △	▽ ▽
Biodiversity based on climate & habitat space (species/km^2)	▽ ▽	▽ ▼	▽ ▽	▽ ▽	▪ ▽	▽ ▼		▽ ▽	▽ ▼	▽ ▽	▽ ▼	▪ ▽	▽ ▼

Increase > 50% : ▲	Increase > 10%: △	Change ±10% : ▪	Decrease > 10%: ▽	Decrease > 50%: ▼

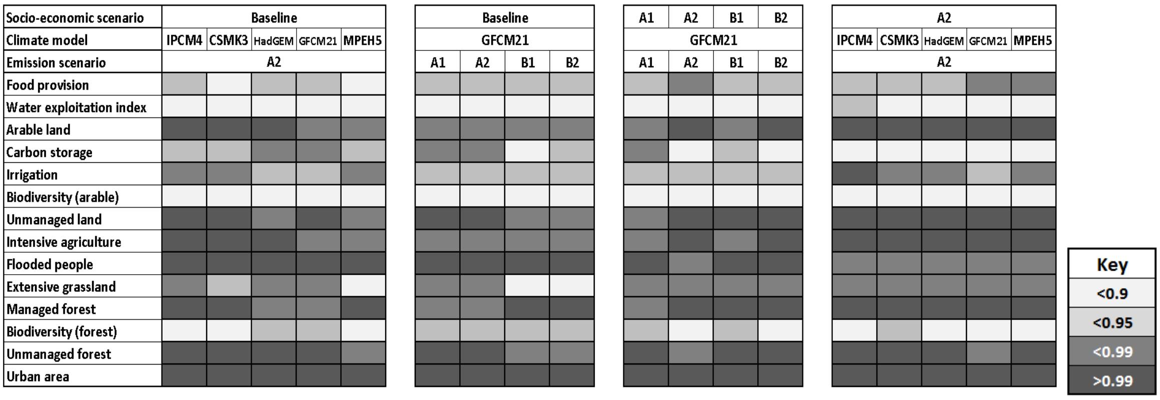
Supplementary Figure 1: Differences between single sector and integrated model impact indicators for the five European regions used in the Europe Chapter of the IPCC AR5[1]. Positive differences indicate that the integrated model produces higher values than single sector models; negative differences indicate that the single sector model values are greater. Both positive and negative differences are presented relative to baseline levels at the regional scale. Based on the IPCM4 climate model combined with baseline or future socio-economics.



Supplementary Figure 2: Schematic showing the linkages between the sectoral models, representing cross-sectoral interactions, within the CLIMSAVE IAP. Adapted from reference 10 in main text.



Supplementary Figure 3: Statistical difference between the single sector and integrated model results based on Lin's concordance correlation coefficient[29]. Thresholds based on McBride[43].



Supplementary Figure 4: Map of the five IPCC regions[44] as they are represented within the CLIMSAVE IAP grid cells. All black areas are in the "Alpine" region.

Additional References

30. Reginster, I., Rounsevell, M. Scenarios of future urban land use in Europe. *Environ. Plan. B – Plan. & Des.* **33,** 619-636 (2006).

31. Trnka, M. *et al.* Simple snow cover model for agrometeorological applications. *Agric. For. Meteorol.* **150,** 1115-1127 (2010).

32. Audsley, E., Pearn, K.R., Harrison, P.A., Berry, P.M. The impact of future socio-economic and climate changes on agricultural land use and the wider environment in East Anglia and North West England using a metamodel system. *Clim. Chang.* **90,** 57-88 (2008).

33. Morales, P. *et al.* Comparing and evaluating process-based ecosystem model predictions of carbon and water fluxes in major European forest biomes. *Glob. Chang. Biol.* **11-12,** 2211-2233 (2005).

34. Holman, I.P. *et al.* A regional, multi-sectoral and integrated assessment of the impacts of climate and socioeconomic change in the UK. *Clim. Chang.* **71,** 9-41 (2005).

35. Annetts, J.E., Audsley, E. Multiple objective linear programming for environmental farm planning. *J. Oper. Res. Soc.* **53,** 933-943 (2002).

36. Döll, P., Kaspar, F., Lehner, B. A global hydrological model for deriving water availability indicators: model tuning and validation. *J. Hydrol.* **270,** 105-134 (2003).

37. Mokrech, M. *et al.* Regional impact assessment of flooding under future climate and socio-economic scenarios for East Anglia and North West England. *Clim. Chang.* **90,** 31-55 (2008).

38. Vafeidis, A.T. *et al.* A new global coastal database for impact and vulnerability analysis to sea-level rise. *J. Coast. Res.* **24(4),** 917-924 (2008).

39. Sutherst, R.W., Maywald, G.F., Bottomley, W., Bourne, A. CLIMEX v2 user's guide. *CSIRO Entomol.* **12-13,** 281-299 (2001).

40. Harrison, P.A., Berry, P.M., Henriques, C., Holman, I.P. Impacts of socio-economic and climate change scenarios on wetlands: linking water resource and biodiversity meta-models. *Clim. Chang.* **90,** 113-139 (2008).

41. Sitch, S. *et al.* Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Glob. Chang. Biol.* **9,** 161-185 (2003).

42. Sallaba, F., Lehsten, D., Seaquist, J., Sykes, M.T. A rapid NPP meta-model for current and future climate and CO_2 scenarios in Europe. *Ecol. Model.*, **302,** 29-41 (2015).

43. McBride, G. B. *A Proposal for Strength-of-Agreement Criteria for Lin's Concordance Correlation Coefficient*. NIWA Client Report to Ministry of Health (HAM2005-062), National Institute of Water & Atmospheric Research Ltd, Hamilton, New Zealand (2005).

44. Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Mücher C.A., Watkins J.W. A climatic stratification of the environment of Europe. *Glob. Ecol. Biogeog.* **14,** 549-563. (2005).